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A THEORETICAL AND EXPERIMENTAL THERMAL ANALYSIS TO DETERMINE WALL RATIOS FOR A 30MM TACTICAL BARREL

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U.S. ARMY ARMAMENT COMMAND

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A combined theoretical-experimental analysis procedure is presented in the determination of wall ratios for a 30mm tactical barrel. Preliminary efforts for this task were devoted to the design of a single-shot barrel fixture; whereas, the current effort addresses the task of designing a barrel capable of withstanding prolonged automatic fire. The final result of this study is a recommended 30mm tactical barrel configuration based on thermal and pressure stress analyses for a prescribed firing schedule.

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INTRODUCTION

The design of gun barrel wall ratios at any axial location is determined by the combined thermal and pressure stresses to which the barrel will be subjected. These stresses are defined by the type of propellant, material properties, projectile configuration and firing schedule. Therefore, in order to design a structurally sound barrel, experimental thermal and pressure data must be available.

Initial or preliminary work on the design of a 30mm barrel was performed[1] on the AMC30 on the basis of propellant data from Hercules[2] and gas convection coefficients from XM-140[3] analyses. As a result of this effort, a single-shot barrel was designed.

OBJECTIVE

The purpose of the current study was to design a 30mm tactical barrel configuration capable of performing satisfactorily under an extended firing schedule. At present, the firing capacity is limited to one 12-round burst. Since future plans include the firing of a more severe schedule, an extreme schedule has been arbitrarily defined as 500 total rounds, in 10-round bursts, with 30-second cooling periods between bursts, at a rate of 240 round per minute. This study is directed toward the task of designing a barrel to satisfy the above firing schedule.

---

[1]Progress Report, "Gun Barrel Thermal Structural Model," under X.O. 512211-5007, by Mr. Darrel Thomsen, Dr. C.C. Chu, and Dr. W.J. Leech.

[2]Letter from G.I. Anderson, Hercules, Inc., to CG WECOM, ATTN: SWERR-W-A, Tom Redling, dated 14 Jun 72.

[3]Adams, D.E., et al., "Design Studies of the XM-140 Barrel," Cornell Aeronautical Laboratory, Inc., Feb 1967.

EXPERIMENTAL ANALYSIS

The 30mm AMCAWS weapon was fired for 7 rounds. The initial purpose was to fire the full capability of the gun, a 12-round burst. However, because hardware problems were encountered, only 7 rounds were fired. The barrel used has a 3-stage configuration, that is, the outside diameters are 1.57, 2.55, and 3.5 inches, with steps occurring at 31 and 63 inches, measured from the muzzle end. Therefore, only 3 axial locations indicated significant temperature rises in 7 rounds; these locations were identified at 3, 15, and 28 inches from the muzzle end, all with an O.D. of 1.57 inches.

These firing data were converted from millivolts to temperatures, °F, via computer program 1, listed in the appendix, and the output plot is given in Figure 1. On the basis of these data, effective propellant gas temperatures and convection coefficient values were obtained by the procedure outlined in the theoretical analysis section.

THEORETICAL ANALYSIS

During the firing of each round, a portion of the heat input entering into the bore is stored in the barrel, and part of this heat is removed from the outer barrel surface. An instantaneous energy balance for any axial location can be written in the following form:

$$q_{in} = q_{stored} + q_{out}$$

Semantically, heat input into the barrel must be equal to the amount of heat stored in the barrel plus the amount of heat dissipated to the surrounding environment. The q terms are defined as follows:

$$q_{in} = h_g A_b (T_g - T_b)$$

where

h_g = mean heat transfer coefficient, BTU/hr - ft^2 - °F
A_b = bore surface area, ft^2
T_g = mean gas temperature, °F
T_b = bore temperature, °F

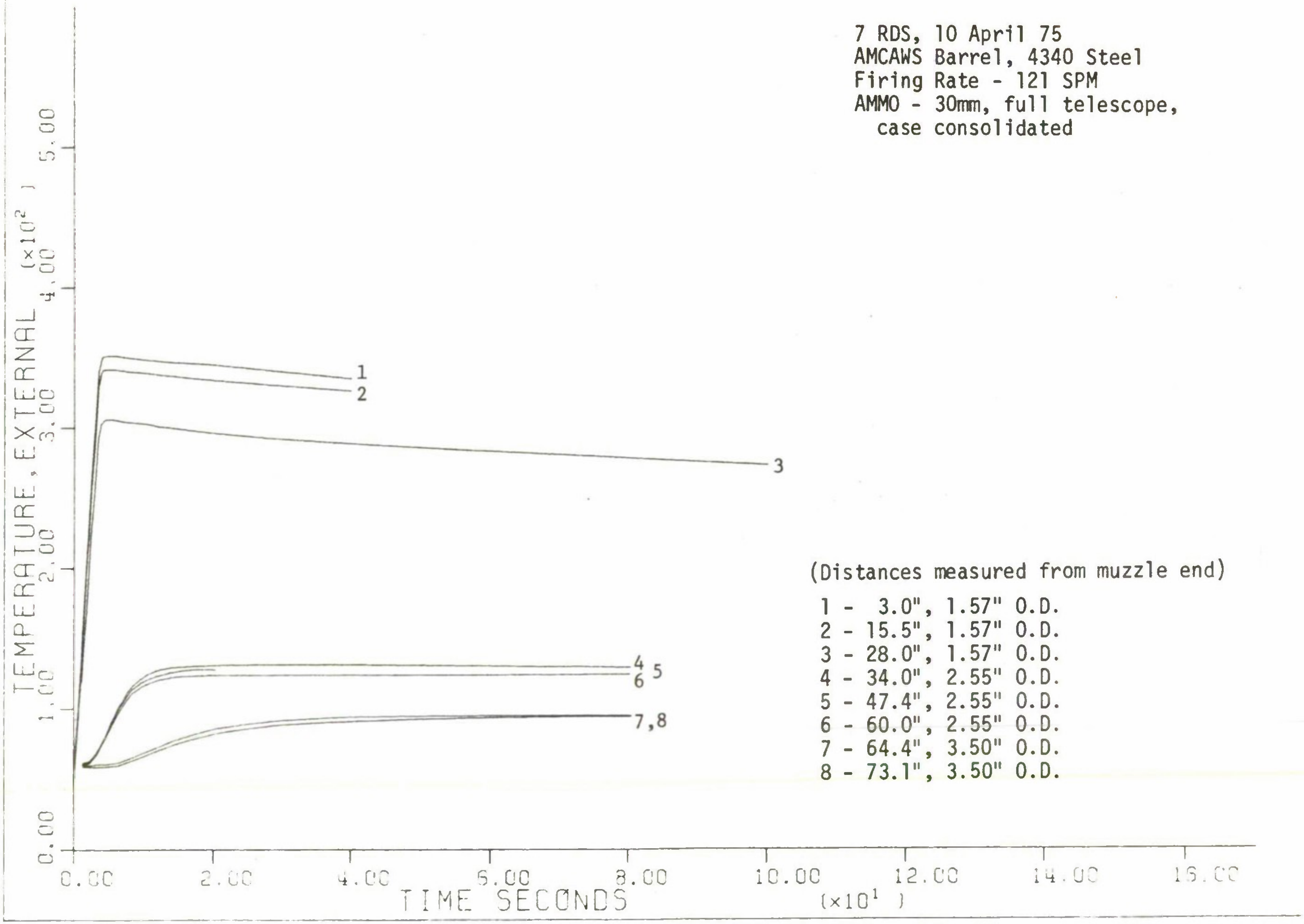
7 RDS, 10 April 75
AMCAWS Barrel, 4340 Steel
Firing Rate - 121 SPM
AMMO - 30mm, full telescope,
case consolidated
(Distances measured from muzzle end)
1 - 3.0", 1.57" O.D.
2 - 15.5", 1.57" O.D.
3 - 28.0", 1.57" O.D.
4 - 34.0", 2.55" O.D.
5 - 47.4", 2.55" O.D.
6 - 60.0", 2.55" O.D.
7 - 64.4", 3.50" O.D.
8 - 73.1", 3.50" O.D.
TEMPERATURE, EXTERNAL (×10²)
0.00
1.00
2.00
3.00
4.00
5.00
TIME SECONDS (×10¹)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
1
2
3
4
5
6
7,8

FIGURE 1

and

$$q_{stored} = mc\,\frac{dT}{d\theta}$$

where

m = mass of barrel, lb_m

c = specific heat of barrel, BTU/lb_m - °F

$\frac{dT}{d\theta}$ = time rate of change of temperature, °F/hr.

and

$$q_{out} = h_o A_s (T_o - T_s) + \varepsilon \sigma A_s (R_o{}^4 - R_s{}^4)$$

where

h_o = dissipation convection coefficient, BTU/hr - ft^2 - °F

A_s = outside barrel surface area, ft^2

T_o = outside barrel surface temperature, °F

T_s = temperature of surrounding environment, °F

ε = surface emissivity

σ = Stephan-Boltzmann constant, BTU/hr - ft^2 - °R^4

R_o = outside barrel surface temperature, °R

R_s = temperature of surrounding environment, °R

The radiation term, $\varepsilon \sigma A_s(R_o{}^4 - R_s{}^4)$, can be disregarded in this analysis, since the radiation effect is insignificant at the temperature levels attained in 7 rounds of firing. The T_b term in q_{in} can be defined as

$$T_b = T_o + \Delta T$$

where ΔT = the temperature difference across the barrel wall, that is, the barrel can be treated as a mass-type calorimeter with the bore temperature being defined as the outer barrel surface temperature plus a radial temperature gradient. Looking at two distinct times in the firing schedule, one can write these equations as follows:

$$h_g A_b (T_g - T_{o1} - \Delta T_1) = mc \left.\frac{dT}{d\theta}\right|_1 + h_{o1} A_s (T_{o1} - T_s) \quad (1)$$

$$h_g A_b (T_g - T_{o2} - \Delta T_2) = mc \left.\frac{dT}{d\theta}\right|_2 + h_{o2} A_s (T_{o2} - T_s) \quad (2)$$

where the subscripts 1 and 2 refer to distinct times on the time versus temperature curve. After equation (1) has been expanded, it becomes

$$h_g (2\pi r_i \ell)(T_g - T_{o1} - \Delta T_1) = \rho\pi(r_o^2 - r_i^2)\ell c \left.\frac{dT}{d\theta}\right|_1 + h_{o1}(2\pi r_o \ell)(T_{o1} - T_s) \quad (1)$$

where

r_i, r_o, ℓ, and ρ are inside radius, outside radius, length, and density of the barrel, respectively. Regrouping yields the following equation:

$$h_g(T_g - T_{o1} - \Delta T_1) = [\rho(r_o^2 - r_i^2)\, c \left.\frac{dT}{d\theta}\right|_1 + 2 r_o h_{o1}(T_{o1} - T_s)]/2r_i$$

Defining KA1, KB1, and K_1,

$$KA1 = \rho(r_o^2 - r_i^2)\, c \left.\frac{dT}{d\theta}\right|_1$$

$$KA2 = 2 r_o h_{o1}(T_{o1} - T_s)$$

and

$$K_1 = (KA1 + KB1)/2r_i$$

Equation (1) now becomes

$$h_g(T_g - T_{o1} - \Delta T_1) = K_1 \quad (1)$$

Similarly,

$$h_g(T_g - T_{o2} - \Delta T_2) = K_2 \quad (2)$$

Define A as follows:

$$A = \left.\frac{dT}{d\theta}\right|_1 \Big/ \left.\frac{dT}{d\theta}\right|_2$$

and assuming that the $d\theta$'s are very nearly the same size

where

$$A = \Delta T_1/\Delta T_2$$

then

$$\Delta T_2 \cong \Delta T_1/A$$

Now, collecting terms and solving equations (1) and (2) simultaneously yields

$$h_g = (K_1 - K_2)/[\Delta T_1(1/A - 1) + (T_{O2} - T_{O1})] \quad (3)$$

Substituting equation (3) into equation (1), one obtains the following:

$$T_g = \Delta T_1 + K_1/h_g + T_{O1} \quad (4)$$

The next step is to select $\left.\frac{dT}{d\theta}\right|_1$ and $\left.\frac{dT}{d\theta}\right|_2$. If one can fit an accurate curve to the experimental temperature data, the derivatives can be evaluated analytically at two distinct points. Otherwise, a discrete set of derivatives can be determined. These two derivatives, $\left.\frac{dT}{d\theta}\right|_1$ and $\left.\frac{dT}{d\theta}\right|_2$, should reflect the changes in temperature early on the time versus temperature curve and toward the end of the curve; but, prior to the quasi, steady-state condition, respectively. The initial value of ΔT_1 is generally selected based on previous experience. Once $\left.\frac{dT}{d\theta}\right|_1$, $\left.\frac{dT}{d\theta}\right|_2$, and ΔT_1 are known, mean values of h_g and T_g can then be determined. With the computer program 2, listed in the appendix, equations (3) and (4) can be quite readily solved. These two values, $\bar{h}_g$ ang $\bar{T}_g$, can be used to solve for the transient, radial temperature distribution for any particular firing schedule and firing rate by input of these values into computer program 3, listed in the appendix. This program employs an implicit, finite-difference algorithm, which is extremely efficient and accurate. Refinement on $\bar{h}_g$ and $\bar{T}_g$ can be made after the temperature output is compared with experimental data. This is accomplished by an iteration process in which ΔT_1 is varied in computer program 2 based on the calculated value obtained in computer program 3.

DISCUSSION OF RESULTS

Mean values $\bar{h}_g$ and $\bar{T}_g$ were obtained from the experimental data taken for the three axial locations, 3, 15.5, and 31 inches (measured from the muzzle end), that gave good temperature response in the 7 rounds. With the use of these values, various wall thicknesses at the three locations were investigated. The outside barrel surface temperature responses for this and a previous parametric wall ratio study are shown in Figure 2. The top center legend defines the firing schedule, and the lower right legend describes axial location, wall thickness, and $\bar{h}_g$ and $\bar{T}_g$ values. The x and y axis labels define the time and temperature in the respective units. The curves for the axial location near the breech end are based on $\bar{h}_g$ and $\bar{T}_g$ values from previous analyses [2,3] since the 7-round firing schedule did not produce significant temperature rise near the breech end. These particular curves in addition to several others that resulted from input values $\bar{h}_g$ and $\bar{T}_g$ taken from Hercules[2] and from XM-140[3] studies are shown in Figure 3. The legends and captions are self-explanatory. On the basis of the temperature results and the pressure data available, an elastic thermal and pressure stress analysis was performed for the breech end location and for the 33-inch location (measured from the muzzle end). Peak total equivalent stresses were within the dynamic[4] yield stress of 108,000 psi for CR-MO-VA steel at 1200°F.

A proposed barrel design is given in Figure 4. This was developed essentially on the basis of the 7 rounds of experimental data, except for the breech end, which is designed as explained above. However, an extended firing schedule of at least 50 rounds should be performed from which more accurate bore boundary condition data can be obtained. These data should be applied to a more optimum design of future 30mm tactical barrels for varying firing requirements.

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[2]Letter from G.I. Anderson, Hercules, Inc., to CG WECOM, ATTN: SWERR-W-A, Tom Redling, dated 14 Jun 72.
[3]Adams, D.E., et al., "Design Studies of the XM-140 Barrel", Cornell Aeronautical Laboratory, Inc., Feb 1967.
[4]"Dynamic Properties of Superalloys at Elevated Temperatures," Technical Report RE-TR-71-75, Research Directorate, Weapons Laboratory, WECOM, February 1972.

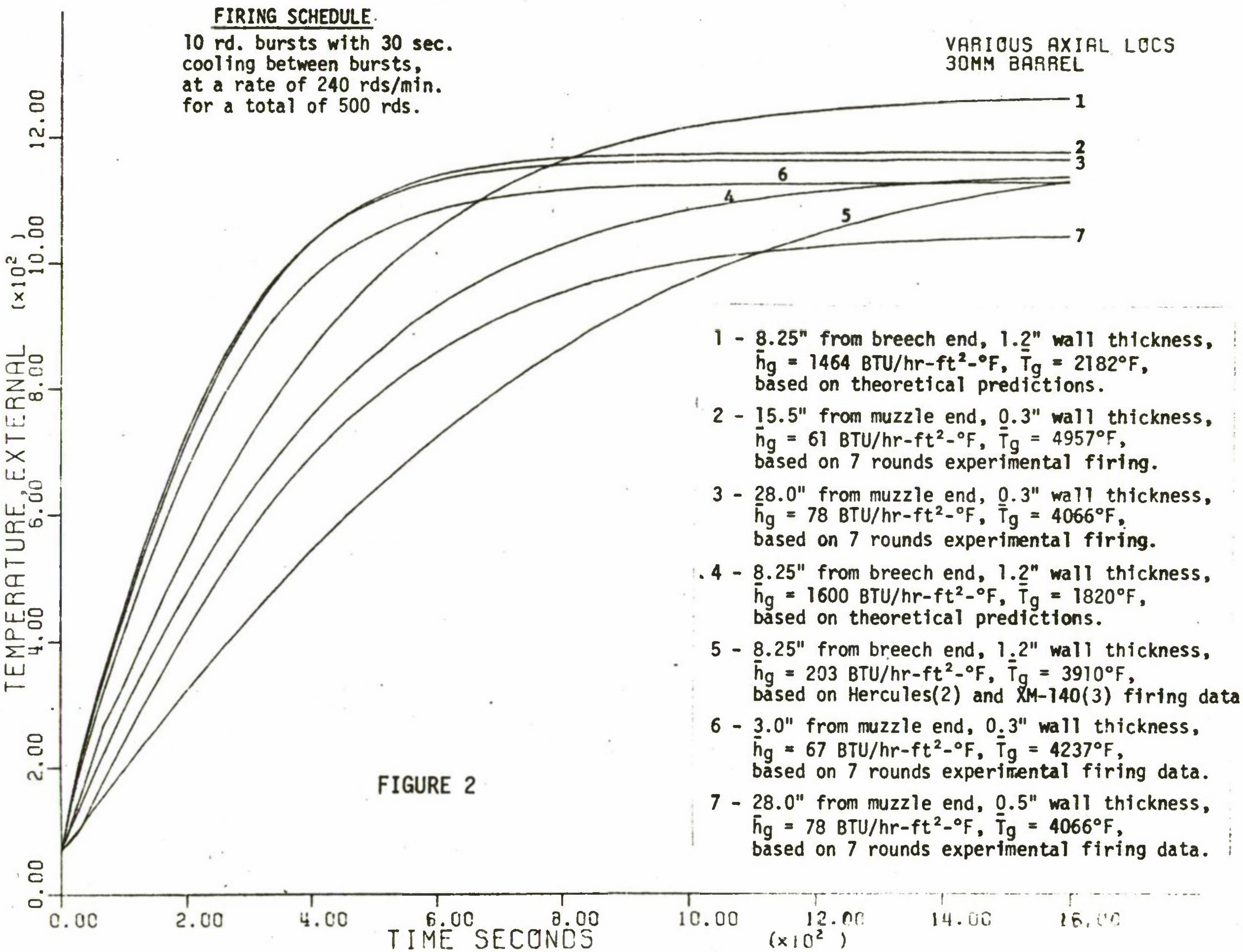
FIRING SCHEDULE
10 rd. bursts with 30 sec. cooling between bursts, at a rate of 240 rds/min. for a total of 500 rds.
VARIOUS AXIAL LOCS
30MM BARREL
1
2
3
4
5
6
7
1 - 8.25" from breech end, 1.2" wall thickness, $\bar{h}_g$ = 1464 BTU/hr-ft²-°F, $\bar{T}_g$ = 2182°F, based on theoretical predictions.
2 - 15.5" from muzzle end, 0.3" wall thickness, $\bar{h}_g$ = 61 BTU/hr-ft²-°F, $\bar{T}_g$ = 4957°F, based on 7 rounds experimental firing.
3 - 28.0" from muzzle end, 0.3" wall thickness, $\bar{h}_g$ = 78 BTU/hr-ft²-°F, $\bar{T}_g$ = 4066°F, based on 7 rounds experimental firing.
4 - 8.25" from breech end, 1.2" wall thickness, $\bar{h}_g$ = 1600 BTU/hr-ft²-°F, $\bar{T}_g$ = 1820°F, based on theoretical predictions.
5 - 8.25" from breech end, 1.2" wall thickness, $\bar{h}_g$ = 203 BTU/hr-ft²-°F, $\bar{T}_g$ = 3910°F, based on Hercules(2) and XM-140(3) firing data.
6 - 3.0" from muzzle end, 0.3" wall thickness, $\bar{h}_g$ = 67 BTU/hr-ft²-°F, $\bar{T}_g$ = 4237°F, based on 7 rounds experimental firing data.
7 - 28.0" from muzzle end, 0.5" wall thickness, $\bar{h}_g$ = 78 BTU/hr-ft²-°F, $\bar{T}_g$ = 4066°F, based on 7 rounds experimental firing data.
TEMPERATURE, EXTERNAL (×10²)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
TIME SECONDS (×10²)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00

FIGURE 2

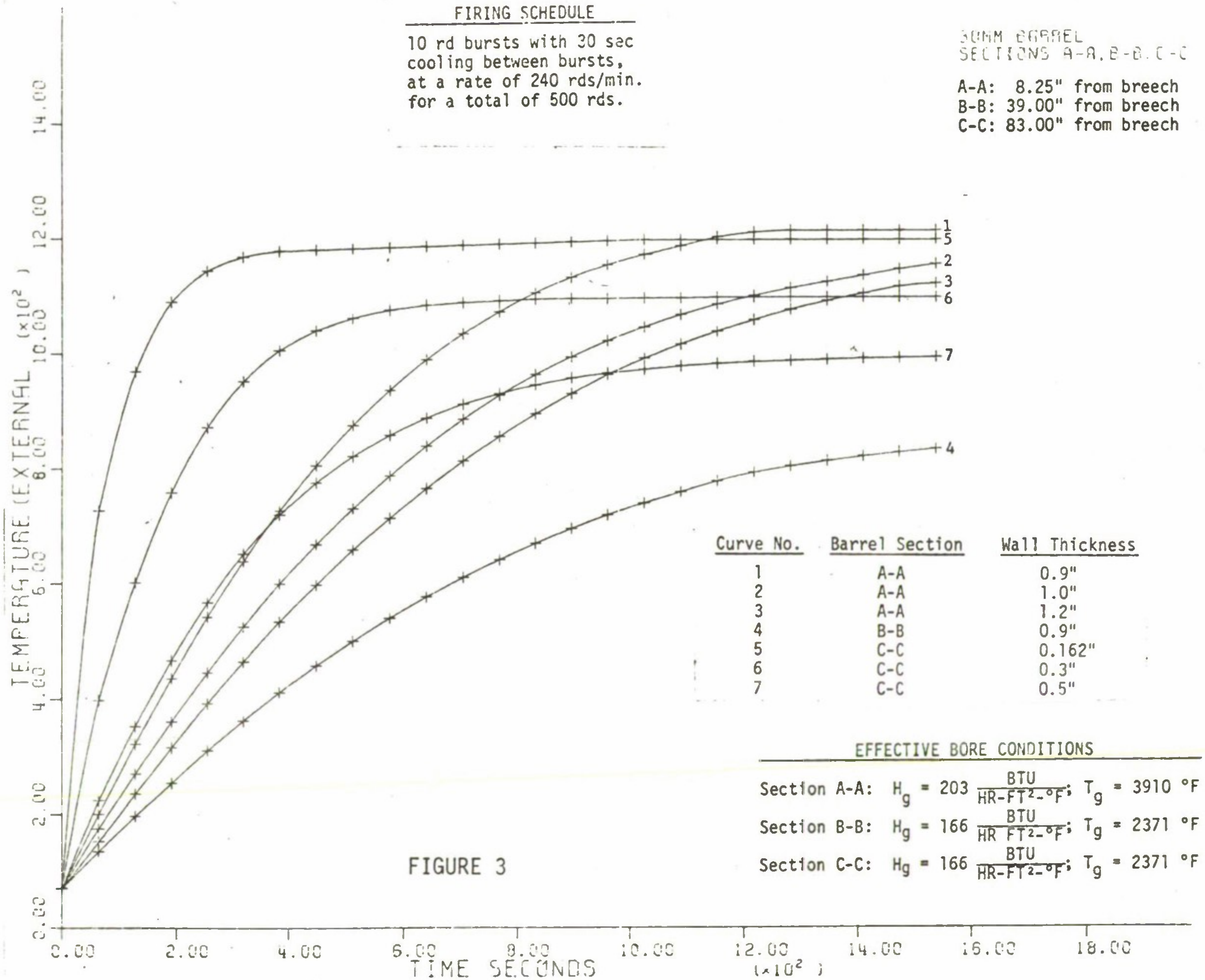
FIRING SCHEDULE
10 rd bursts with 30 sec cooling between bursts, at a rate of 240 rds/min. for a total of 500 rds.
30MM BARREL SECTIONS A-A, B-B, C-C
A-A: 8.25" from breech
B-B: 39.00" from breech
C-C: 83.00" from breech
Curve No. | Barrel Section | Wall Thickness
1 | A-A | 0.9"
2 | A-A | 1.0"
3 | A-A | 1.2"
4 | B-B | 0.9"
5 | C-C | 0.162"
6 | C-C | 0.3"
7 | C-C | 0.5"
EFFECTIVE BORE CONDITIONS
Section A-A: $H_g = 203 \frac{BTU}{HR\text{-}FT^2\text{-}°F}$; $T_g = 3910$ °F
Section B-B: $H_g = 166 \frac{BTU}{HR\ FT^2\text{-}°F}$; $T_g = 2371$ °F
Section C-C: $H_g = 166 \frac{BTU}{HR\text{-}FT^2\text{-}°F}$; $T_g = 2371$ °F
TEMPERATURE (EXTERNAL $(\times 10^2)$
TIME SECONDS $(\times 10^2)$
1
2
3
4
5
6
7
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00

FIGURE 3

PROPOSED 30MM TACTICAL BARREL

(CR-MO-VA STEEL)

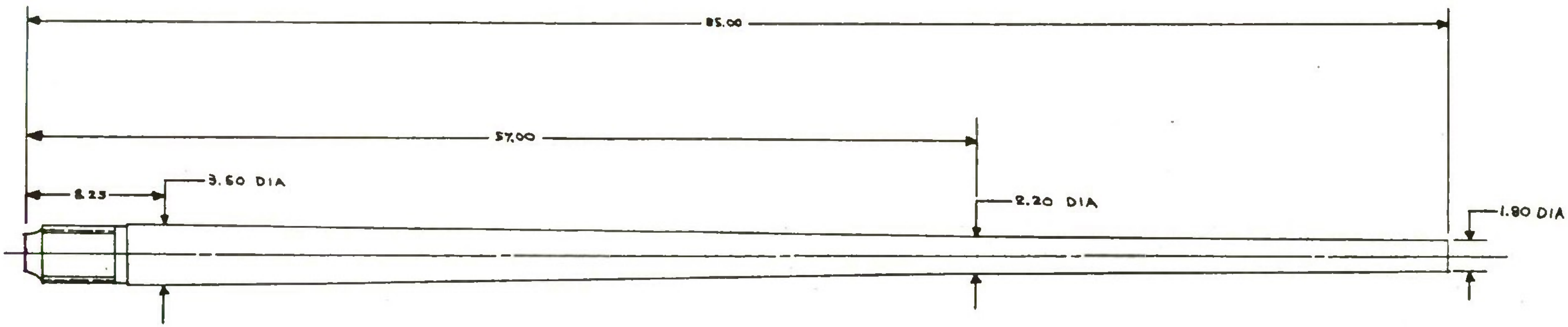

FIGURE 4

APPENDIX

Computer Program 1

```
      DIMENSION DATAX(99),DATAY(99)
      COMMON/BLK1/F1,F2,F3,C1,C2,J,ITYPE
      COMMON/BLK2/NPTS(20)
      READ 1,NSETS,ITYPE
    1 FORMAT(2I5)
C     ITYPE=0 MEANS DATA IS TEMPERATURE.
C     ITYPE=1 MEANS DATA IS MILLIVOLTS.
      READ 2,(NPTS(J),J=1,NSETS)
    2 FORMAT(16I5)
      READ 3,F1,F2,F3,C1,C2
    3 FORMAT(5F10.5)
      II=1
      J=II
      NPT=NPTS(J)
    6 READ 4,(DATAX(I),DATAY(I),I=1,NPT)
      CALL CONVRT(DATAX,DATAY)
      II=II+1
      J=II
      NPT=NPTS(J)
      IF(II.GT.NSETS) GO TO 5
      GO TO 6
    4 FORMAT(10F8.3)
    5 CALL EXIT
      END
```

```
      SUBROUTINE CONVRT(OATAX,OATAY)
      REAL OATAX(99),OATAY(99)
      COMMON/BLK1/F1,F2,F3,C1,C2,J,ITYPE
      COMMON/BLK2/NPTS(20)
  600 NP=NPTS(J)
      PRINT 400
  400 FORMAT(1H1)
      IF(ITYPE.EQ.0) GO TO 403
      PRINT 402
  402 FORMAT(6X,'TIME',8X,'MILLIVOLTS',5X,'TEMPERATURE(OEG.F)')
      GO TO 405
  403 PRINT 404
  404 FORMAT(6X,'TIME',23X,'TEMPERATURE(OEG.F)')
      OO 11 I=1,NP
      PRINT 12,OATAX(I),DATAY(I)
   12 FORMAT(1F10.1,15X,1F20.1)
   11 CONTINUE
      GO TO 99
  405 OO 10 I=1,NP
      IF(OATAY(I).GT.C1) GO TO 5
      IF(OATAY(I).GT.C2) GO TO 6
      FACTOR=F3
      GO TO 7
    5 FACTOR=F1
      GO TO 7
    6 FACTOR=F2
    7 TEMP=OATAY(I)
      OATAY(I)=OATAY(I)*FACTOR+32.
      PRINT 401,OATAX(I),TEMP,OATAY(I)
  401 FORMAT(1F10.1,1F15.3,1F20.1)
   10 CONTINUE
   99 IF(J.EQ.1) GO TO 100
      GO TO 200
  100 CALL GRAPH(NP,OATAX,OATAY,0,1,9.0,7.0,200.,0.0,
     2200.,0.0,'TIME SECONOS$','TEMPERATURE,EXTERNAL$',
     3'VARIOUS AXIAL LOCS$','30MM BARREL$')
      GO TO 300
  200 CALL GRAPH(NP,OATAX,DATAY,0,1,0.0,7.0,200.,0.0,
     2200.,0.0,'TIME SECONOS$','TEMPERATURE,EXTERNAL$',
     3'VARIOUS AXIAL LOCS$','30MM BARREL$')
  300 RETURN
      END
```

APPENDIX

Computer Program 2

```
      IMPLICIT REAL*8(A-Z)
      READ 1,RHO,TA,TW1,TW2,DTDT1,DTDT2,HO1,HO2,RI,RO,CP,DT2
      PRINT 1,RHO,TA,TW1,TW2,DTDT1,DTDT2,HO1,HO2,RI,RO,CP,DT2
    1 FORMAT(8F10.5/6F10.5)
      CC=RHO*CP*(RO**2-RI**2)
      KA1=CC*DTDT1*3600.
      KA2=CC*DTDT2*3600.
      KB1=HO1*2.*RO*(TW1-TA)
      KB2=HO2*2.*RO*(TW2-TA)
      K1=(KA1+KB1)/(2.*RI)
      K2=(KA2+KB2)/(2.*RI)
      A=DTDT1/DTDT2
      C3=TW2-TW1
      HG=(K1-K2)/(C3+DT2*(1./A-1.))
      TG = 1./HG*((KA2 + KB2)/(2.*RI)) + TW2 + DT2
      BDYR=15.0/HG
      PRINT 2,HG,TG,BDYR
      PRINT 3,KA1,KA2
      PRINT 3,KB1,KB2
      PRINT 3,K1,K2
      PRINT 3,C3
    3 FORMAT(10X,3F20.10)
    2 FORMAT(10X,'HG=',F10.5,10X,'TG=',F10.5,10X,'BOYR=',F10.5)
      CALL EXIT
      END
```

APPENDIX

Computer Program 3

```
              C  ONE-DIMENSIONAL TRANSIENT HEAT CONDUCTION PROGRAM (HT-2A)
              C  PROGRAMMED BY A.M.CLAUSING.  VERSION = 1 JULY 1970
              C  THIS PROGRAM IS A GENERAL PROGRAM FOR THE SOLUTION OF CONDUCTION
              C  PROBLEMS WITH TEN OR LESS REGIONS INCLUDING INTERFACIAL RESISTANCES
              C  BETWEEN REGIONS
              C
 0001               DIMENSION ANS(199),NPLOT(11),TT(150)
              C**DEFINITION OF LABELED COMMON -- BLK1,BLK2, AND BLK3
 0002               COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
 0003               COMMON /BLK2/ RADII(11),NODES(10),XKZ(99),BETA(10),CP(10),RHO(10),
                   2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)
 0004               COMMON /BLK3/  ISYM,XMIN,XMAX,YMIN,YMAX,
                   2IPLOT(11), TIM(150),TTB(150) , TTO(150)
              C
              C**INITIALIZATION OF VARIABLES NOT LOCATED IN LABELED COMMON
 0005               DATA ANS,TNUM,TDENOM,DZ,DTIMEX,DDTX,IX,NBODY/.2,.4,1.0,2.0,
                   2195*.0, .0, 1., 1., .0005,.25, 3, 1/
              C
              C**READ CHARACTERISTICS OF PROBLEM -- RAW INPUT DATA
              C
              C**DEFINITION OF NAM AND NAM1
 0006               NAMELIST /NAM/ T,ISYM,YMAX,YMIN,XMAX,XMIN,TNUM,TDENOM,ANS,
                   2NODES,XKZ,BETA,CP,RHO,BDYR,EMISS,DZ,    DTIMEX,DDTX,IX,NBODY,CPZ,
                   3RHOZ,XKRZ,RADII,A,ITB
                   4/NAM1/DTIMEX,DDTX,DZ,II,NBODY,IX,XKRZ,RHOZ,CPZ,EMISS,TNUM,TDENOM,
                   5ISYM,XMAX,XMIN,YMAX,YMIN,NODES,ANS,A,ITB,IPLOT
 0007               DIMENSION TIMEF(250),F(250)
 0008               READ 100,N
 0009         100   FORMAT(I5)
 0010               READ 200, (TIMEF(I),F(I),I=1,N)
 0011         200   FORMAT (8F10.5)
 0012               PRINT 202
 0013         202   FORMAT (8X,'TIMEF',25X,'F')
 0014               PRINT 203, (TIMEF(I),F(I),I=1,N)
 0015         203   FORMAT (5X,F10.5,16X,F10.5)
 0016         26    READ(5,NAM)
              C
              C**CALCULATE DIMENSIONLESS LUMPED PARAMETERS, HX(I) AND C(I)
 0017               CALL LUMP (II,NBODY,DZ)
              C
              C**WRITE PROBLEM PARAMETERS
 0018               WRITE(6,3)
 0019         3     FORMAT(29H1HEAT TRANSFER PROGRAM HT-2A /27H PROGRAMMED BY A.M.CLAU
                   2SING/30H CRANK-NICOLSON ALGORITHM
                   3    /26H VERSION = 1 JULY 1970     ///25H THE INPUT PARAMETERS ARE)
 0020               WRITE(6,NAM1)
 0021               WRITE(6,5)
 0022         5     FORMAT(7H0REGION,3X5HIBODY,3X 9HRADII(FT),5X6HDR(FT),5X8HBDYR(FT),
                   26X2HCP,8X3HRHO,8X2HKZ,6X4HBETA )
 0023               WRITE(6,7) (J,IBODY(J,1),IBODY(J,2),RADII(J),DR(J),BDYR(J),CP(J),
                   2RHO(J),XKZ(J), BETA(J), J=1,NBODY)
 0024         7     FORMAT(I3,I9,I4,3E12.3,  F10.3,2F10.1,F11.6)
 0025               I = NBODY + 1
```

```
0026          WRITE(6, 9)I,RADII(I),BDYR(I)                                       00440
0027     9    FORMAT(I3,12X,E12.3,12X,E12.3//)                                    00450
0028          WRITE(6,11)                                                         00460
0029     11   FORMAT(3X1HI,7X5H H(I), 12X4HC(I), 12X4HT(I),  7X6HRADIUS )         00470
0030          WRITE(6,13)(I, H(I),C(I),T(I),RI(I),    I=1,II)                     00480
0031     13   FORMAT(I4,2E16.4,F13.2,F13.5)                                       00490
         C                                                                        00500
         C**CALCULATE OR INITIALIZE VARIOUS QUANTITIES --- SAVE T(I) AND DTIMEX   00510
0032          TSEC = D7**2*RHOZ*CPZ*3600./XKRZ                                    00520
0033          IIM1 = II - 1                                                       00530
0034          IIM2 = II - 2                                                       00540
0035          IIP1 = II + 1                                                       00550
0036          IF(ANS(1).GT..0) GO TO 131                                          00560
0037          DO 133 I=1,198
0038       133 ANS(I) = ANS(I)/TSEC                                               00580
0039          ANS(1) = -ANS(1)                                                    00590
0040       131 DO 15 I=1,IIP1                                                     00600
0041     15   TT(I) = T(I)                                                        00610
0042          ATIME = DTIMEX                                                      00620
0043          DDDTX=DDTX                                                          00630
0044          N=0                                                                 00640
0045          IANS=1                                                              00650
0046          TAUT = .0                                                           00660
0047          ITIM=0
         C                                                                        00680
         C**START OF SOLUTION OF PROBLEM                                          00830
         C  POINT OF MAJOR LOOP ENTRY -- SN25(NO NEW DTIMEX), SN24(NEW DTIMEX)    00840
0048     24   DO 19 I=2,IIM1                                                      00850
0049     19   CX(I) = C(I)/DTIMEX*2.                                              00860
0050       25 CALL CHANGE(NBODY,TSEC,TAUT,II,IX,N)                                00870
0051          TIME=TAUT*TSEC
0052          HX(1)=RADII(1)/BDYR(1)
0053          CALL LINEAR(TIME,TIMEF,F,FACTOR)
0054          HX(1)=HX(1)*FACTOR
0055          CALL SOLVE (IIM1,IIM2,II,NBODY,BETA)                                00880
0056          N = N + 1                                                           00890
0057          TAUT = TAUT +DTIMEX                                                 00900
         C**END OF TIME STEP                                                      01020
         C**IF TIMEX=DDDTX DOUBLE TIME INCREMENT                                  01030
         C 21  IF(TAUT.LT.DDDTX) GO TO 29                                         01040
         C     IRET = 1
         C     DTIMEX = DTIMEX*2.
         C     DDDTX = 2.*DDDTX
         C     WRITE(6,31) DTIMEX,TAUT
         C  31 FORMAT(//57H TIME INCREMENT DOUBLED. NEW DIMENSIONLESS INCREMENT 1 01090
         C    2S = ,F7.4/36H THE CURRENT DIMENSIONLESS TIME IS =,F7.4)            01100
0058          IF(FACTOR .LT. .5 ) GO TO 260
0059          IF(FACTOR .GT. .5 ) GO TO 280
0060       260 DTIMEX = .005
0061          GO TO 300
0062       280 DTIMEX = .0005
0063       300 IRET = 1
0064          GO TO 33                                                            01110
```

```
0065        29    IRET = 2                                                      01120
            C                                                                   01130
            C**IF TAUT.GT.ANS(IANS) PRINT TEMPERATURE DISTRIBUTIONS ETC.        01140
0066        33    IF(TAUT.LT.ANS(IANS)) GO TO (24,25),IRET                      01150
0067              IANS = IANS + 1                                               01160
0068              CALL RESULT(TAUT,IIM1,II,TNUM,TDENOM,DZ,NBODY,ANS,IANS,       01170
                 1DTIMEX,ITP1,IIM2,ITIM)
0069              IF(ANS(IANS).NE.0) GO TO (24,25),IRET                         01190
            C                                                                   01200
            C**RESET INITIAL CONDITION AND TIME INCREMENT -- READ NEXT CASE -- SN26  01210
0070        35    DTIMEX = ATIME                                                01220
0071              DO 37 I=1,ITP1                                                01230
0072        37    T(I) = TT(I)                                                  01240
0073              GO TO 26                                                      01250
0074              END                                                           01260
```

```
0001          SUBROUTINE LUMP(II,NBODY,DZ)                                        01270
0002          COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)      01280
0003          COMMON /BLK2/ RADII(11),NODES(10),XKZ(99),BETA(10),CP(10),RHO(10),  00100
             2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)   01300
      C                                                                           01310
      C**THIS SUBROUTINE CALCULATES THE DIMENSIONLESS LUMPED PARAMETERS           01320
0004          AZ=RHOZ*CPZ*DZ**2                                                   01330
0005          CI = .0                                                             01340
0006          C(1) = .0                                                           01350
0007          IF(BDYR(1).EQ..0) GO TO 3                                           01360
0008          HX(1) = RADII(1)/BDYR(1)                                            01370
0009          H(1) = HX(1)                                                        01380
0010          IBODY(1,1) = 2                                                      01390
0011          GO TO 5                                                             01400
0012    3     IBODY(1,1) = 1                                                      01410
0013    5     RI(1) = RADII(1)                                                    01420
      C                                                                           01430
      C**BEGINNING OF LOOP TO CALCULATE C(I) AND H(I) FOR NBODY REGIONS(J)        01440
0014          DO 4 J=1,NBODY                                                      01450
0015          DRP = RADII(J+1) - RADII(J)                                         01460
0016          DR(J) = DRP/FLOAT(NODES(J)-1)                                       01470
0017          IBODY(J,2) = IBODY(J,1) + NODES(J) - 1                              01480
0018          IB = IBODY(J,1)                                                     01490
0019          IE = IBODY(J,2) - 1                                                 01500
0020          RI(IB) = RADII(J)                                                   01510
      C                                                                           01520
      C**CALCULATION OF C(I) AND H(I) FOR REGION J                                01530
0021          AJ = RHO(J)*CP(J)*DR(J)/AZ                                          01540
0022          C(IB) = AJ*(RI(IB) + DR(J)/4.)/2.+ CI                               01550
0023          BJ = XKZ(J)/(XKRZ*DR(J))                                            01560
0024          DO 1 I=IB,IE                                                        01570
0025          H(I) = BJ*(RI(I)+DR(J)/2.)                                          01580
0026          RI(I+1) = RI(I) + DR(J)                                             01590
0027    1     C(I+1) = AJ*RI(I+1)                                                 01600
0028          C(IE+1) = AJ*(RI(IE+1)-DR(J)/4.)/2.                                 01610
      C                                                                           01620
      C**CECK TO SEE IF INTERFACIAL RESISTANCE IS ZERO AND PROCEED ACCORDINGLY    01630
0029          IF(BDYR(J+1).EQ..0) GO TO 2                                         01640
0030          CI = .0                                                             01650
0031          IBODY(J+1,1) = IBODY(J,2) + 1                                       01660
0032          HX(IE+1)= RI(IE+1)/BDYR(J+1)                                        01670
0033          H(IE +1) = HX(IE+1)                                                 01680
0034          GO TO 4                                                             01690
0035    2     CI = C(IE+1)                                                        01700
0036          IBODY(J+1,1) = IBODY(J,2)                                           01710
0037    4     CONTINUE                                                            01720
0038          IF(BDYR(NBODY+1).NE..0) GO TO 11                                    01730
0039          II = IE + 1                                                         01740
0040          GO TO 13                                                            01750
0041    11    II = IE +2                                                          01760
0042          C(II) = .0                                                          01770
0043    13    H(II) = .0                                                          01780
0044          RI(II)= RADII(NBODY + 1)                                            01790
```

```
              C
              C**CALCULATE THE DIMENSIONLESS RADIUS RII
 0045               DO 16 I=1,II
 0046         16    RII(I) =  (RI(I) - RADII(1))/(RADII(NBODY+1) - RADII(1))
 0047               RETURN
 0048               END
```

```
      SUBROUTINE LINEAR(A,X,Y,VV)
      DIMENSION X(1),Y(1)
      I=1
C   1 IF(Y(I+1) .LT. Y(I)) GO TO 100
C         USE FOLLOWING IF AS Y INCREASES X INCREASES
   10 IF(A-X(I))3,2,2
C         USE FOLLOWING IF AS Y INCREASES X DECREASES
C 100 IF(A-X(I))2,2,3
    2 I=I+1
      GO TO 10
    3 I=I-1
      VV=Y(I)*(A-X(I+1))/(X(T)-X(I+1))+Y(I+))*(A-X(I))/(X(I+1)-X(I))
      RETURN
      END
```

```
0001             SUBROUTINE SOLVE (IIM1,IIM2,II,NBODY,BETA)
0002             DIMENSION GE(150),FE(150),DE(150),BETA(10),BE(150), BI(150)
0003             COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
           C
           C**CORRECT THE BODY CONDUCTANCES FOR VARIABLE CONDUCTIVITIES
0004       1     DO 3  J=1,NBODY
0005             IB = IBODY(J,1)
0006             IE= IBODY(J,2) - 1
0007             DO 3  I=IB,IE
0008       3     HX(I) = H(I)*(1. + BETA(J)*(T(I) + T(I+1))/2.)
           C
           C**START OF ELIMINATION -- CRANK-NICOLSON ALGORITHM
0009             DO 9 I=2,IIM1
0010             C1 = HX(I) + HX(I-1)
0011             BE(I) = CX(I) + C1
0012       9     BI(I) = CX(I) - C1
0013             GE(2) = BE(2)
0014             FE(2) = (BI(2)*T(2) + HX(2)*T(3) + HX(1)*T(1)*2.)/GE(2)
0015             DO 5 I=3,IIM1
0016             DE(I) = -HX(I-1)/GE(I-1)
0017             GE(I) = BE(I) + HX(I-1)*DE(I)
0018       5     FE(I) = (HX(I)*T(I+1) + HX(I-1)*T(I-1) + BI(I)*T(I) + HX(I-1)*
                2 FE(I-1))/GE(I)
0019             FE(IIM1) = FE(IIM1) + HX(IIM1)*T(II)/GE(IIM1)
           C
           C**BACK SUBSTITUTION
0020             T(IIM1) = FE(IIM1)
0021             DO 7 I=2,IIM2
0022             J = II - I
0023       7     T(J) = FE(J) - DE(J+1)*T(J+1)
0024             RETURN
0025             END
```

```
0001          SUBROUTINE RESULT(TAUT,IIM1,II,TNUM,TDENOM,DZ,NBODY,ANS,IANS,        02180
             2DTIMEX,IIPI,IIM2,ITIM)
0002          DIMENSION TSTAR(150),XM(10),ANS(199),NPLOT(11),Y(500),TT(150)
0003          COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)       02210
0004          COMMON /BLK2/ RADII(11),NODES(10),XKZ(99),BETA(10),CP(10),RHO(10),   00100
             2EMISS,RHOZ,CPZ,XKRZ,BOYR(11),RI(150),RII(150),DR(10),A(9),ITR(11)    02230
0005          COMMON /BLK3/  ISYM,XMIN,XMAX,YMIN,YMAX,                             00120
             21PLOT(11), TIM(150),TTB(150) , TTO(150)                              02241
          C                                                                        02250
          C**CALCULATE DIMENSIONAL TIME,HEAT FLOWS PER UNIT DEPTH, TSTARS, M'S     02260
          C**AND WEIGHTED AVERAGE TEMPERATURE.  PRINT THESE QUANTITIES.            02270
0006           CALL TAVE(II,IIP1)                                                  02280
0007           TSEC  = DZ**2 * RHOZ* CPZ * 3600./ XKRZ                             02290
0008          TIME = TAUT * TSEC                                                   02300
0009          QIN = HX(1)*XKRZ*6.2832*(T(1) - T(2))                                02310
0010          QOUT = HX(IIM1)*XKRZ*6.2832*(T(IIM1) - T(II))                        02320
0011          HOUT=HX(IIM1)*XKRZ/RI(IIM1)
0012          HCON=XKRZ/BOYR(NBODY+1)
0013          HRA=HOUT-HCON
0014          HIN=HX(1)*XKRZ/RADII(1)
0015          DO 1 I=1,IIP1                                                        02330
0016      1   TSTAR(I) = (T(I) - TNUM)/TDENOM                                      02340
0017          DO 3 J=1,NBODY                                                       02350
0018      3   XM(J) = DR(J)**2/(DTIMEX*DZ**2)                                      02360
0019          WRITE(6,5) TAUT                                                      02370
0020      5   FORMAT(////22H0 DIMENSIONLESS TIME =,F7.3,10X28HHEAT FLOW PER FT (   02380
             2BTU/HR-FT),10X48HCOMBINED CONVECTION COEFFICIENT (BTU/HR-FT**2-F))   02390
0021          WRITE(6,7) TIME,QIN,QOUT,HOUT,HRA                                    02400
0022      7   FORMAT(22H  REAL TIME (SECONDS)=,F11.3,3X4HQIN=E12.3,7H  QOUT=,E12   02410
             2.3,3X7H HR+HC=,E12.3,3X3HHR=,E12.3)                                  02420
0023          WRITE(6,9) (XM(I),I=1,NBODY)                                         02430
0024      9   FORMAT(39H0 M VALUES FOR REGIONS 1 THRU NBODY ARE,10F6.2)            02440
0025          WRITE(6,8) HIN
0026      8   FORMAT(25H0  HIN  (BTU/HR-FT**2-F)=,10F8.2)
          C                                                                        02450
          C**PRINT THE DIMENSIONAL TEMPERATURES                                    02460
0027          WRITE(6,11) T(1),IIM1,(T(I),I=2,IIM1)                                02470
0028     11   FORMAT(  /35H0THE DIMENSIONAL TEMPERATURES ARE  /6H T(1)=,F10.2/     02480
             213H T(2) THRU T(,I3,9H)  FOLLOW/(5F10.2,5X,5F10.2))                  02490
0029          WRITE(6,13)II, T(II), T(IIP1)                                        02500
0030     13   FORMAT(3H T(,I3,2H)=,F12.2,6X,7HT(AVE)=,F12.2)                       02510
          C                                                                        02520
          C**IF ANS(30).NE..0, PRINT THE DIMENSIONLESS TEMPERATURES                02530
          C         WRITE(6,15)TSTAR(1),IIM1,(TSTAR(I),I=2,IIM1)                   02550
          C       WRITE(6,13) II,TSTAR(II), TSTAR(IIP1)                            02560
          C15   FORMAT(  /35H0THE DIMENSIONLESS TEMPERATURES ARE/6H T(1)=,F10.2/   02570
          C      213H T(2) THRU T(,I3,9H)  FOLLOW/(5F10.3,5X,5F10.3))              02580
          C       PLOT OF AVG TEMP. VS TIME
0031          REAL DATAAX(150), DATAAY(150)
0032          ITIM = ITIM + 1
          C       TAVE = T(IIP1)
0033          TT(ITIM) = T(IIP1)
0034          TTB(ITIM) = T(2)
```

```
            TTO(ITIM) = T(IIM1)
            TIM(ITIM) = TAUT*TSEC
            IF (IPLOT(11) .EQ.0) GO TO 18
            IF(ANS(IANS).NE.0) GO TO 18
            DO 17 J = 1, ITIM
            DATAAY(J) = TT(J)
   17       DATAAX(J) = TIM(J)
            CALL GRAPH (ITIM, DATAAX, DATAAY, 3, 1, 8.0, 8.0, 0.0, 0.0,
           20.0, 0.0,  'TIME SECOND;', 'TEMPERATURE (AVE) F;',
           2'TRANSIENT TEMP.;', 'VARIOUS RADII;')
   18       CONTINUE
C          PLOT BORE TEMP. VS TIME
            IF (IPLOT(10) .EQ.0 ) GO TO 19
            IF(ANS(IANS).NE.0) GO TO 19
            REAL DATAXA(150), DATAYA(150)
            DO 21 J = 1,ITIM
            DATAYA(J) = TTB(J)
   21       DATAXA(J) = TIM(J)
            CALL GRAPH (ITIM, DATAXA, DATAYA, 3, 1, 8.0, 8.0, 0.0, 0.0, 0.0,
           20.0, 'TIME SECONDS;','TEMPERATURE (BORE) F',
           2'TRANSIENT BORE TEMP;','CALCULATED DATA;')
   19       CONTINUE
C         PLOT BARREL EXTERNAL TEMP. VS TIME
            IF (IPLOT (9) .EQ. 0 ) GO TO 25
            IF (ANS (IANS).NE.0) GO TO 25
            REAL DATAIX(150), DATAIY(150)
            DO 23 J = 1,ITIM
            DATAIY(J) = TTO(J)
   23       DATAIX(J) = TIM(J)
            CALL GRAPH (ITIM, DATAIX,  DATAIY,  3, 1, 8.0, 8.0, 0.0, 0.0,
           20.0, 0.0, 'TIME SECONDS;','TEMPERATURE(EXTERNAL) F;', '
           2TRANSIENT EXTERNAL TEMP.;', 'CALCULATED DATA;')
   25       CONTINUE                    /
C PLOT TEMP VS RADII
            REAL DATAX(50), DATAY(50)
            IF (ANS (IANS).NE.0)RETURN
            DO 16 I = 2,IIM1
            DATAY(I-1) = T(I)
   16       DATAX(I-1) = RI(I)
            CALL GRAPH (IIM2, DATAX, DATAY, 3, 1, 8.0, 8.0, 0.0, 0.0, 0.0,0.0,
           2'RADIUS FT;', 'TEMPERATURE F;', 'THERMAL DATA ;', 'L.P. CHAMBER;')
C
            RETURN
            END
```

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0001              SUBROUTINE TAVE(II,IIP1)
0002              COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
            C
            C**CALCULATE WEIGHTED AVERAGED TEMPERATURE AND STORE IT IN T(IIP1)
0003              SUM = .0
0004              SUM2 = .0
0005              DO 39 I=1,II
0006              SUM = SUM + C(I)*T(I)
0007        39    SUM2 = SUM2 + C(I)
0008              T(IIP1) = SUM/SUM2
0009              RETURN
0010              END
```

```
      SUBROUTINE CHANGE (NBODY,TSEC,TAUT,II,IX,NNN)
      DIMENSION HZ(11),N1(11),N2(11)
      COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)
      COMMON /BLK2/ RADII(11),NODES(10),XKZ(99),BETA(10),CP(10),RHO(10),
     2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RI1(150),DR(10),A(9),ITB(11)
C
C     J     = NUMBER OF R'S WHICH ARE TEMP. OR TIME DEPENDENT
C     N1(J)= RESISTOR NUMBER -- N1(J) = J1
C     N2(J)= RESISTOR TYPE
C     HZ(J)= RESISTOR'S INITIAL VALUE
C     A     = ARRAY CONTAINING COEFFICIENTS FOR FUNCTIONS, EXPONENTS ETC.
C     TSEC = CONVERSION FACTOR (REAL TIME IN SECONDS = TIMEX*TSEC)
C     EXPO1= EXPONENT N WHERE H = HZ*ABS(T(J1) - T(J1+1))**EXPO1
C     ITB  = ARRAY CONTAINING TYPE KEY FOR ALL BOUNDARY RESISTORS
C     TYPE = 1   H = CONSTANT
C     TYPE = 2   H = HZ*F3(TIME)
C     TYPE = 3   H = HZ*(DT)**EXPO1
C     TYPE = 4   H = HR + HC
C     TYPE = 5 H = HZ*F5(TIME) -- F5 IS A PERODIC RECTANGULAR WAVE
C
C  STORE INITIAL VALUES AND DETERMINE WHICH RESISTORS ARE NOT OF TYPE 1
      IF(TAUT.GT..0) GO TO 1
      N=0
      N8 = IFIX( A(8) )
      N9 = IFIX( A(9) )
      T1 = T(1)
      TII = T(II)
      HR = EMISS*.1714E-8/XKRZ
      EXPO1 = A(7)
      J = 0
      IF(ITB(1).EQ.1) GO TO 7
      J = 1
      N1(1) = 1
      N2(1) = ITB(1)
      HZ(1) = HX(1)
    7 DO 5 I=1,NBODY
      IF(ITB(I+1).EQ.1) GO TO 5
      J = J + 1
      N1(J) = IBODY(I,2)
      N2(J) = ITB(I+1)
      J1 = N1(J)
      HZ(J) = HX(J1)
    5 CONTINUE
C
C**POINT OF ENTRY FOR TIME.GT.ZERO -- CALCULATE NEW BDY TEMPERATURES
    1 TIME = TAUT*TSEC
      T(1) = T1*(1. + A(1)*SIN(A(2)*TIME))
      T(II)=TII*(1.+TIME*A(3)+A(4)*TIME**2)
C
C**IF ALL R'S ARE CONSTANTS RETURN OTHERWISE RECALCULATE THOSE CHANGING
      IF(J.EQ.0) RETURN
      DO 11 I=1,J
      J1 = N1(I)
```

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 0033             DTEMP = ABS(T(J1)-T(J1+1))                                              03540
 0034             IF(DTEMP.EQ..0) DTEMP=1.                                                03550
 0035             M = M2(I)                                                               03560
 0036             GO TO (11,12,13,14,15,16,17),M                                          03570
 0037       12    HX(J1) = HZ(I) *(1. + A(5)*SIN(A(6)*TIME))                              03580
 0038             GO TO 11                                                                03590
 0039       13    HX(J1) = HZ(I)  *     DTEMP            **EXPO1                          03600
 0040             GO TO 11                                                                03610
 0041       14    TA = T(J1) + 460.                                                       03620
 0042             TB = T(J1+1) + 460.                                                     03630
 0043             HX(J1) =  HP*PI(J1)     *(TA**2 + TB**2)*(TA + TB)                      03640
                2  + HZ(I) * DTEMP ** EXPO1                                               03650
 0044             GO TO 11                                                                03660
 0045       15    IF(J.EQ.0) HX(J1) = HZ(I) * A(5)                                        03670
 0046             IF(J.EQ.N8) HX(J1) = HZ(I)                                              03680
 0047             IF(N.EQ.N9) N =-1                                                       03690
 0048             N = N + 1                                                               03700
 0049             GO TO 11                                                                03710
 0050       16    GO TO 11                                                                03720
 0051       17    GO TO 11                                                                03730
 0052       11    CONTINUE                                                                03740
 0053             NN1 = NNN + 1                                                           03750
 0054             IF((MOD(NN1,IX).NE.0).OR.(J.EQ.0)) RETURN                               03760
 0055             DO 21 I=1,J                                                             03770
 0056             J1 = N1(I)                                                              03780
 0057       21    T(II+I+1) = HX(J1) * XKRZ / RI(J1)                                      03790
 0058             RETURN                                                                  03800
 0059             END                                                                     03810
```

```
0001           BLOCK DATA                                                         03820
          C                                                                       03830
          C**INITIALIZATION OF LABELED COMMON TO DEFAULT VALUES                   03840
0002           COMMON /BLK1/ T(150),C(150),CX(150),H(150),HX(150),IBODY(10,2)     03850
0003           COMMON /BLK2/ RADII(11),NODES(10),XKZ(99),BETA(10),CP(10),RHO(10), 00100
              2EMISS,RHOZ,CPZ,XKRZ,BDYR(11),RI(150),RII(150),DR(10),A(9),ITB(11)  03870
0004           COMMON /BLK3/  ISYM,XMIN,XMAX,YMIN,YMAX,                           00120
              2IPLOT(11), TIM(150),TTB(150) , TTO(150)                            03881
0005           DATA ISYM,XMIN,XMAX,YMIN,YMAX,EMISS,RHOZ,CPZ,XKRZ,XKZ,BETA,CP,RHO/ 03890
              2 0, .0, 1., .0, 1., 1., 490.,.11, 10., 99*10., 10*.0,10*.11,10*490 03900
              3./,NODES,T,BDYR/10*5, 1.,149*.0,11*.0/,A,ITB/6*.0,.25,2*.0,11*1/   03910
              4,IPLOT/8*0,1,1,1/
0006           END                                                                03920
```

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Prepared by: Philip D. Benzkofer

Technical Report: R-TR-75-023

34 pages, Including Figures

A combined theoretical-experimental analysis procedure is presented in the determination of wall ratios for a 30mm tactical barrel. Preliminary efforts for this task were devoted to the design of a single-shot barrel fixture; whereas, the current effort addresses the task of designing a barrel capable of withstanding prolonged automatic fire. The final result of this study is a recommended 30mm tactical barrel configuration based on thermal and pressure stress analyses for a prescribed firing schedule.

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